A HIGH INTENSITY NEUTRON GENERATOR

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ABSTRACT. A 400 KV deuteron D.C. accelerator of Cockroft-Walton type, for production of neutrons by $d-d$ and $d-t$ reactions, is described. Special features and principal operating characteristics of this generator are discussed.

I. INTRODUCTION

A 400 KV Cockroft-Walton type deuteron accelerator, designed for delivering 5 mA of deuteron ion beam, had been planned, fabricated and installed in this institute and been operating regularly and efficiently for the last eighteen months. The exothermic nature of (d, d) and (d, t) reaction and its high cross section made this type of generator compact and low voltage one. The development and easy availability of the targets of deuterium and tritium gas absorbed in Zirconium or Titanium, have given a strong impetus for building this compact low voltage unit for producing fairly strong sources of monoenergetic γ-free neutrons in the 3.5 MeV and 14 MeV range. In fact, several reports (Peck and Eubank, 1955; Bergstralh, *et al*., 1953, Lorram, *et al*., 1957; Bonner, *et al*., 1959) of such generators have appeared in recent years in the literature. In our case, the aim was to produce and accelerate the most intense beam of deuteron ion that can be brought to bear on the target of absorbed gas quite safely. To achieve this end, we have developed the ion source and the lens system in such a way as to focuss an unanalysed deuteron beam of 2.5 mA. Also the cooling of the target was thoroughly investigated so that in the end we could focuss on the target a beam current of more than 1 mA. The principal characteristics of our generators are (i) its high ion beam consisting of more than 90% of monatomic ions, obtained by suitable modifications of ion source. (*ii*) The high voltage is obtained by multiplying a high frequency voltage in a cascade column. This is done both for the purpose of economy and reduction in size as also for reduction in ripples and load effect. The filament supply of the rectifier column is separate and also of high frequency. (iii) The cooling of the absorbed gas target is directly by refrigerant or liquid nitrogen, with an eye to the maximum possible heat transfer, so as to bear as high an ion beam as possible on the target without exceeding its safe temperature of 70° at any time even locally.

II. C–W VOLTAGE GENERATOR

The voltage generator is, as usual, a voltage multiplying circuit based on the original Greinacher (1921) circuit, as improved progressively by Cockroft-Walton (1932), Gradstein (1936), Arnold (1950), Lorrain (1949), etc. Particularly the masterly analysis of voltage multiplying circuits, by Bowers (1939), and by Mitchell (1945) have contributed handsomely towards the understanding and improvements of this type of voltage generator. Following the development by Douma and Brekoo at the Philips laboratory and the suggestions made by Lorrain, radio frequency was adopted for both the main High Voltage and also for heating the filaments. We discarded the practice of using power frequencies or other near frequencies In addition to the marked economy in cost and equipments, a considerable reduction in size was achieved by the use of radio-frequencies. Also a decided improvement in the matters of ripples on the output voltage and of voltage drop with load, was achieved through its use Although the presence of voltage ripple is not a serious handicap to its use as a neutron generator, still the smallest value of ripple voltage is an advantage in achieving a sharply defined energy. In fact, the higher the frequency and the larger the capacity, the smaller will be the ripple and load effect.

The output voltage of a *c-w* multiplier unit can be written as

$$V = 2nE - \Delta V - \delta V.$$

$$= 2nE - \frac{i}{fc}\left(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{1}{6}n\right) - \frac{i}{fc}\left[\frac{n(n+1)}{2}\right]$$

$$= 2nE - \frac{i}{fc}\left[\frac{2}{3}n^3 + n^2 - \frac{n}{6} + \frac{1}{2}\right]$$

$$= 2nE - \frac{i}{fc}\cdot\frac{n}{3}(2n+1)(n+1) \qquad \text{.. (1)}$$

where
n = number of stages in the multiplier column
E = peak input voltage
ΔV = voltage drop due to load
δV = ripple voltage
i = current drain on the high voltage
f = operating frequency
C = condenser value

The effect of higher condenser and frequency values is apparent. So also the desirability of limiting the n value. In practice, there is an upper limit to the frequency that can be usefully employed. Also the value of the condenser is decided by the bulk and the cost. Some compromise is made between these conflicting factors and it was found that 100 Kc/s and 400 Kc/s are two of the best practical values for the mains and filament heating frequencies. The theoretical values of ripple voltage is 3 5 V per mA of load current, and of voltage drop due to load is 22 volt per mA, assuming the value of $n = 7$ and $c = .05 \mu f$.

The unit of a multiplying circuit of our generator is shown as in the Fig 1. The C-W generator has several pairs of Eimac 100 R radiation cooled rectifier arranged in cascade supported by equal numbers of condensers arranged in column. The tubes are encased in leaklight perspex tubes coupled to each other by aluminium domes. The other arrangements of the column are not far different from that adopted at Philips laboratory. The filaments of the tubes are heated by 350 Kc/s power coupled by ferroxcube core transformer Plate power supply frequency is 75 Kc/s. The isolation of the two frequencies from each other was obtained by means of LC circuits resonant at the filament heating frequency. The multiplier circuit is supplied by a master oscillator and power amplifier—the output of which is amplified by a very high Q resonant coil, which in turn feeds the multiplier column. The bleeder resistance is a chain of five resistances of 100 meg ohms each, which draws a current of 800 μA at maximum voltage of 400 KV. This column of resistances is also encased in a perspex tube to be filled with silicone oil for better stability.

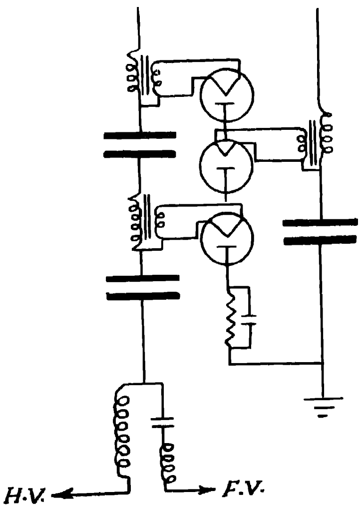


Fig. 1.

The total resistance of the column was measured within an error of 0.1% It was observed that the resistance column value remained fairly constant over a long period of time. Percentage of ripple was determined by means of an oscilloscope, taking the output from the low voltage end of the resistance column. The measured value was found to be 7 volt per mA of load current. The voltage drop with 7 mA of load current is 140V. This agrees within close limits with our theoretical value as calculated from the formulae shown in Eq. 1. The stabilisation of the high voltage was achieved by the stabilisation of the input R.F. voltage from the oscillator. This in turn was done by taking a small fraction of the voltage output and using them to correct any change in the D.C. plate voltage of the oscillator The power to the filaments of the transmitter tubes was fed through a magnetic voltage stabiliser. The actual stabilisation achieved in this way was better than 0.1%.

GENERAL ARRANGEMENTS

The plan of the general arrangements of the high tension set, the accelerating unit and the power supplying alternator is shown in the Fig. 2. The accelerator column consists of three numbers of silica tubes. Detailed description of the accelerating tube is given in the following section. The accelerating column

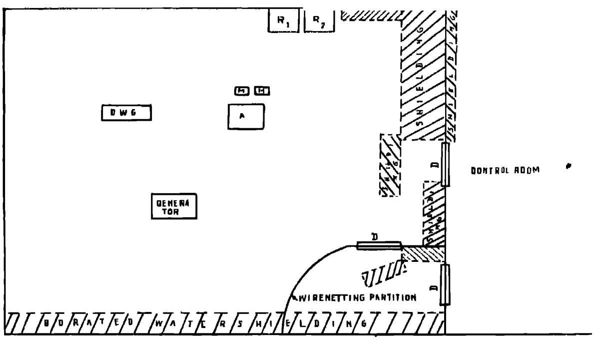


Fig. 2. General plan of layout of C-W Generator

is placed vertically in our case— though we considered the advantages accruing from the horizontal alignment of the column which is very often followed in the case of low voltage accelerator. We are guided in this respect by the ease of assembly and alignment in the vertical system as also the ease of automatically providing high voltage insulation from the ground. The units for supplying power to the ion source and the focussing lens—all should be at high voltage and hence placed in a housing well insulated from ground. The high voltage terminal housing is a polished aluminium dome rounded at corners to prevent corona loss. The four insulating columns for supporting this high voltage terminal are all made of 3″ dia. perspex tube sealed at both ends to prevent penetration of dust and moisture The outside surface of these tubes are treated and polished with silicone fluid D. C. 200 to prevent any adhesion of moisture on them. Inside the high voltage terminal are located (a) the radio-frequency ion source oscillator and its power supply, (b) the extracting voltage supply (0—5 KV), (c) the focussing voltage supply (0-15 KV) and (d) the cooling fans and light arrangements. The precision leak valve and its control together with the gas reservoir are also located inside this dome. Appropriate meters to indicate operation of the above circuits are suitably placed in the dome with clear perspex windows. Control rods in the form of perspex tubes come out of the housing from each circuit. The tubes are operated by remotely controlled system Mirror and telescope arrangements were made to obtain remote view of the H.V. terminal operation, An alternator for supplying power to the units in the high voltage terminal, is placed in a dome similar to the above. The alternator generates 110 V. A C. single phase, 800 cycles frequency. The alternator body is made of aluminium alloy, thereby ensuring a light weight The alternator rotates at 3000 r.p.m. and is driven by a motor placed at ground end and the driving system requires careful designs and high insulations.

In our case this is driven by a 3 H.P. A.C. 3 phase motor with speed of 3000 rpm. The coupling system is a $2\frac{1}{2}''$ dia. perspex tube, 4 ft. long, suitably joined at the ends by means of universal couplings. No speed reduction gears are employed now. This arrangement is marked by simplicity and directness, though it required very careful adjustments at the beginning. An alternate arrangement involving the reduction of speed of rotation of perspex shaft by a factor of 10, is in progress.

ION SOURCE

Several types of ion sources were examined for suitability of their uses in this particular instrument. Of these, two types immediately recommended themselves by reasons of stability, long life and ease of maintenance. One of them is the Radio-frequency ion source and the other the Penning Cold Cathode ion gauge type. For low power consumption, circuit simplicity and compactness, the penning type source seemed better. But for high ion yield, and for high percentage of atomic ion in the beam, R. F. type source has hardly any equal. Since our instrument requirement is for highest atomic ion beam consistent with low gas consumption, R F. ion source became our obvious choice.

In our design, we adopted the Oak Ridge type with some modifications for higher ion yield. The discharge tube is a $1''$ dia. Pyrex glass tube, $6''$ long, sealed to the metal plate by means of gasketed flanged joints. The Extraction canal is of pure aluminium $1/16''$ dia. $\times 3/16''$ long. The cover glass for the canal is of pyrex, —its top grounded flat and polished (Fig. 4). A triode 3/300 tube was used in an ultra-audion circuit to provide a maximum power output of 300 watts at 75 mc/s. The coupling was done by quater wave transmission lines, glass leak to the tube was controlled by a finely adjustable leak valve. A strong magnetic field was provided around the canal tip. The life of the glass tip and the aluminium canal depends greatly on the beam current extracted throughout it. In our case the averge life of the canal and the tip is more than 200 hrs. The part played by cleaning of the discharge tube can not be over emphasised. The method of cleaning by diluted hydrofluoric acid was found to be good and occasional cleaning by this method tended to increase the ion output.

Deuteron currents approaching 4.5 mA at 4 KV extraction potential could be obtained from this ion source. The beam divergence was small enough to be focussed by an electro static lens within a spot of 3-4 mm at a distance of 1 meter. Of course this required increased gas feed to the source and a longer canal diameter. Experiments on monatomic ion percentage in the deuteron beam current showed that quality of glass of the ion source and its annealing conditions have a strong influence on the high monatomic ion percentage. It was also found that after more than 200 hours running, the ion source tended to produce a lesser yield of atomic ion percentage. This is probably due to vitrification of the glass material.

VACUUM SYSTEM

The pumping unit initially consisted of one 4″ oil diffusion pump backed by a rotary mechanical pump having a free air displacement capacity of 140 lit/min. The oil diffusion pump was designed and fabricated by us and it developed an unbaffled pumping speed of 275 lit/sec at 10^{-5} mm Hg. The mechanical pump developed a backing pressure of 6×10^{-4} mm Hg and speed of 0.7 lit/sec when the system was running with no gas load. A refrigerated optical baffle using Freon-22, was employed to trap all the back streaming oil vapour and keep the accelerating tubes and target chamber free from traces of oil vapour. The actual pumping speed developed with this baffle and system was 140 l/sec at 1×10^{-5} mm Hg. To handle increased gas feed to the ion source at the time of increasing ion beam current, and also to handle occasional gas bursts, provision of another 4″ diffusion pump was made. This later pump was designed with an eye to its ability to handle larger throughput. The baffle system of this pump was made in two stage. One was a water baffle and the second a freon cooled refirgerated baffle. The temperature of the water baffle was designed to be of 35°C.

The vacuum measuring gauges consist of one thermo-couple gauge for low vaccum range (1 mm to 10^{-3} mm) and one hot cathode ionisation gauge for high vacuum range (10^{-4} to 10^{-6} mm Hg). Adequate provisions of ion gauge control, interlock system of high vacuum with ion gauge, water flow, refrigerating cooling unit and diffusion pump heater, were arranged. Weston sensitrol relays were freely used for these control. The r.f. ion source at its normal operation consumes nearly 10-15 cc. of gas at atmospheric pressure per hour. This means a leak load on the high vacuum side of the accelerator tube. The ultimate vacuum in the accelerator tube with no gas load, as measured by the ionisation gauge at the ground end of the tube, was 2×10^{-6} mm Hg and the vacuum with the ion source and the system running, was better than 1×10^{-5} mm Hg.

ACCELERATING COLUMN

The accelerating column forms the most important item in the neutron generator. This consists of three silica tubes each of 6″ i/d × 10″ long with wall thickness of 1/4″ and flanged at each end. These are joined together by means of aluminium plates having grooved gasket on each face. The plates and the silica tubes are clamped together and covered by means of ring shaped polished aluminium domes. Each aluminium plate carries a lens. These lenses are formed of spun copper tube, heavily chromium plated. The shape, gap width, diameter and other configuration of the lenses are given in the Fig. 3. Each gap is screened from the silica tubes wall to avoid any accumulation of electrostatic charge by

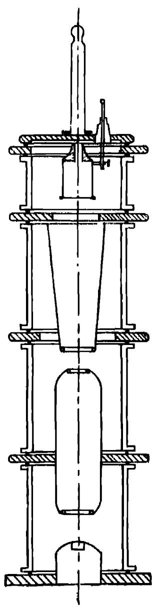


Fig. 3. Ion acceleration column.

the insulator wall. Because of the particular mechanical set up of the lense system, good alignment is automatically assured at the time of assembly. Fig. 4 is a sketch of the focussing electrode together with the ion source assembly. The ion source is mounted on a gasket in a plate on the other side of which the focussing system is integrally mounted by means of a high voltage ceramic seal. The ion

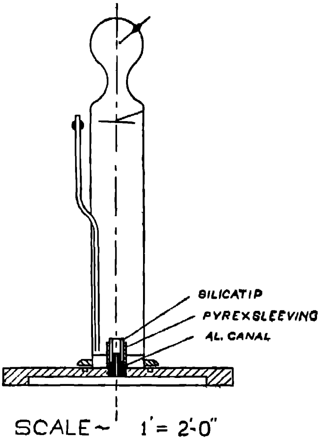


Fig. 4 R. F. ion source.

source can be aligned with respect to the probe canal and the focussing lens by means of a set of removable adjusting screws. These adjustments are to be made when the system is running. The arrangements of the lens system is such that the major part of the accelerating voltage is developed across the last lens gap. As a result the beam is focussed on the target, at a distance of 1 8 metres from the ion source, under all values of high voltage exceeding a certain minimum value. The focal length of the last lens is almost constant irrespective of the voltage on it as it falls on the asymptotic region of the *f-v* curve (Fig 5).

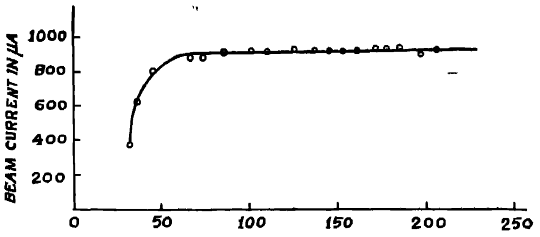


Fig. 5. Deuteron energy in KV.

TARGET ASSEMBLY

As this instrument is a high current one and meant for high neutron flux, the design of the target system, particularly its cooling, calls for careful attention and examination of details. Our instrument is designed to operate with either tritium or deuterium target. For (D, T) reaction, Tritium gas absorbed in titanium and mounted by evaporation on copper, was used. Both the thick and the thin types were employed, depending on the necessity of particular experiments. The useful life of a target depends on the efficiency of the cooling system and its ability to transfer the maximum amount of heat without allowing the target to exceed the safe temperature of 70°C even momentarily. The development of hot spot on the target is to be carefully avoided.

We have used several types of target mountings and cooling arrangements. First one we used is shown in Fig 6(i). The cooling was done by precooled water forced directly on the underside of the target in a jet at a maximum pressure of 30 lbs/sq. in. The target intercepts the beam at an angle of 45°, and also there is an arrangement to rotate the target at a slow rate by means of motor and gear assembly. An offset in the target manifold enabled one to bring the sample for bombardment within 4 cm from the target. The performance of the target is such that at 200 Kv up to 450 μA of unanalysed deuteron beam can be brought to bear on the target. The neutron yield under this condition is about 4×10^{10} n/sec. The target temperature rose up to 70°C. The mechanical pump output was monitored for traces of degassed tritium The target life was understandably short under this condition.

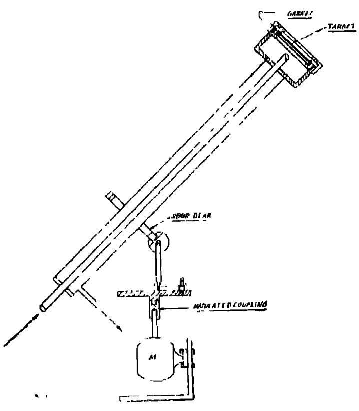
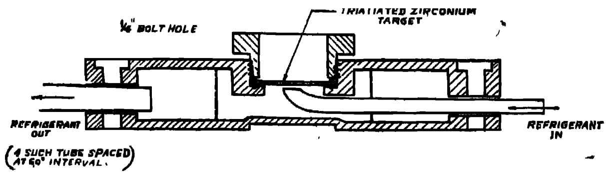


Fig. 6(i). Water-cooled oscillating target.

We changed this target arrangements in favour of another in which cooling is done by means of a refrigerant. The arrangement is shown in Fig. 6(ii). The minimum temperature that the target attains is 8°F. The gas used is Freon-20, and the capacity of the refrigerating unit is more than 4000 BTU/hr. ; under this condition more than 850μA of deuteron beam at 200 KV, was put on the target and continuously operated. For short run not exceeding 1 hr. at a time more



Fig, 6 (ii). Target cooling system. Refrigerant-cooled target

than 1.5 mA was tolerated without exceeding the safe limit of target temperature of 75°C. Temperature measurement was done by means of a pair of differential thermocouple attached to the target. The maximum neutron yield obtained was more than 3 × 10^{11} n/sec. The beam on this target which is not a rotating type, is purposely defocussed on an area of approximately 3/4″, and is thus designed to cover the entire useful area of the target. In this target the bombarding sample can be brought within less than one cm of the target.

Still another type of target cooling was designed for use with liquid nitrogen coolant, but this was discarded in favour of the refrigerant cooled unit in view of the frequent attention that the former type requires. In all these types the main source of trouble is the deposition of carbon, the target assembly due to the traces of oil vapour present from the diffusion pump. This trouble was eliminated in the refrigerant cooled unit by providing a cooler guard ring around the target on which most of the vapour deposit, thus keeping the target free from contamination.

ADJUSTMENT

The ion acceleration system needs very careful adjustments and precise alignment in order to obtain the maximum ion beam on the target. This is important, otherwise several undesirable characteristics will appear. Some of the more important of such unwanted characteristics are :

(i) the radial and axial drift of the focal point of the ion beam, with change in acceleration voltage,

(ii) change or fluctuations of accelerating voltage with variation in load.

These factors were eliminated with proper care in design and alignment. The ion acceleration systems were first mechanically aligned to a high degree of precision with respect to the last lens. This was supplemented by a further adjustment in the running condition. The adjustment was made to make the ion beam maximum and by this method the ion optical axes of the ion source, focussing lens and extraction probe lens were brought in one line.

MEASUREMENT OF ION CURRENT

Accurate measurement of ion beam current free from all ambiguities due to secondary electron emission and additional secondary ion collection, is very important. Due care and precautions were exercised to measure this The most direct way is to use a Faraday cage and this cage was used in preliminary stages to measure the current. When ion beam current is high, the colorimetric method is convenient We have measured the rise in temperature at target, by means of a differential thermocouple. The ion beam current could only be held steady to within 0.5 to 1% under good conditions. The ion current was found to be very sensitive to any change in pressure in the ion acceleration tube and steady beam current could only be obtained if occasional gas bursts in the accelerator tube is kept to a minimum. To this end, twofold means were employed :

(i) keeping the vacuum system scrupulously clean and chromium plating the lens system,

and (ii) using a diffusion pump unit of high enough speed, capable of handling a large thoroughput without undue rise in ambient pressure

NEUTRON FLUX AND SPECTRUM

The neutron flux was measured by three methods .

(i) by means of a calibrated neutron counter

(ii) by means of threshold detectors

and (iii) by means of nuclear emulsion plates.

In the first method, we used a BF_3 counter (containing enriched B^{10}) in a long counter geometry. This counter was previously calibrated very carefully. Its advantage is that it is intensitive to γ-ray and inherently stable and has very low background, and disadvantages are that it is sensitive to neutrons of lower energy and hence could not discriminate against scattered neutron background.

In most of our experiments, the fast neutron flux measurements were made by activation of some selected element, based on neutron threshold reaction. Its main advantages are (i) it is insensitive to neutrons of energy below the threshold, (hence to most of the scattered neutrons) and (ii) it is capable of measuring flux without causing significant perturbation in flux distribution. In our case 9.9 min activity of Cu^{63} (n, 2n) Cu^{62} was used for this flux measurement. The threshold of this reaction is 10.65 MeV and the adopted value of its cross-section is taken to determine any 5.1 min activity of $Cu^{65}(n, \gamma)Cu^{66}$ if it was produced, since the presence of low energy neutron or thermal neutron may cause this later activity to contribute to the total activity and cause errors. However, since Cu^{62} is positron emitter the separation of this activity from that of Cu^{66} is not

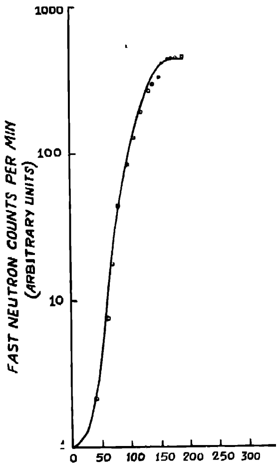


Fig. 7. Neutron yield curve as function of deuteron energy

difficult. Where bombardment time is longer (i.e. more than 30 min) we have used the 14.8 hr. activity of Al^{27} (n, α) Na^{24} having an effective energy of 8.1 MeV for calibration. Na^{24} being both β and γ active, we have measured the β-activity by means of an end window G.M. counter and the γ activity by means of a γ-spectrometer. The results from the two measurements agree closely.

The nuclear emulsion plates were used to measure the neutron fluxes as well as the spectrum of neutrons emerging from D—T reactions. We used Ilford C_2 plate of emulsion thickness of 200μ and these are exposed at an angle of 5° to the incident neutron. The measurement of the proton tracks released by the incoming neutrons in the emulsion, yielded the fast neutron spectra [Figs. 8(i) & 8(ii)] with plate both shielded and unshielded are given in the figure. The spectra from an old target is also given. The presence of D—D neutrons (of 3.5 MeV energy) can be seen.

The degree of reproducibility and accuracy in flux determination by the above methods, have been checked by several independent measurements. A typical determination of the flux by means of several methods is given in Table I.

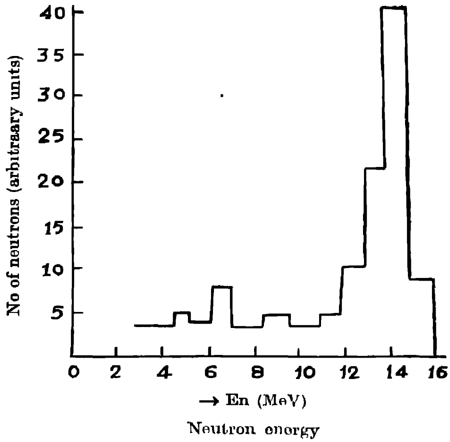


Fig. 8 (i) Spectrum of neutrons from H^3 (d,n, He^4 detector in a channel of water and paraffin shield).

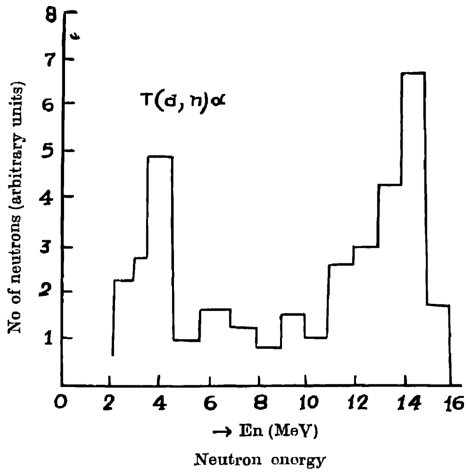


Fig. 8(ii). Spectrum of D–T neutron from an old target . Detector unshielded.

TABLE I

Operational condition	Method of measurement	Value of neutron flux in n/sec.
Deuteron beam Energy – 190 KeV	irradiated Cu foil and measurement of β^+ activity of Cu^{62} from $Cu^{63}(n, 2n)Cu^{62}$ reaction	
Deuteron beam Current - 580 μa	irradiated Al foil and measurement of β^- activity of Na^{24} from $Al^{27}(n, \alpha)Na^{24}$ reaction	8.5×10^{10}
	irradiated Al foil and measurement of 1.38 MeV γ—activity of Na^{24} from the above reaction	8.3×10^{10}
	Nuclear emulsion plate Ilford $C2$ 200μ thick	8.5×10^{10}
	Calibrated BF_3 long counter	9.2×10^{10}
	Calibrated fast neutron counter	8.9×10^{10}

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